1. Basic Earth Structure

Before we begin with a detailed treatment of the various geophysical techniques let’s do a brief overview of Earth structure. We separate this broadly into two parts where we concern ourselves with (1) the Earth’s composition and (2) how the Earth behaves mechanically, loosely defined as either hard solid, liquid, or soft solid.

1.1 Chemical Composition

The basic divisions of the Earth based on chemical composition are as drawn below.

The chemical composition is divided into the following three basic layers.

(1) The crust.

(2) The mantle: which includes the layers called the transition zone and the D" layer. We call the region of the mantle deeper than the transition zone the lower mantle, and that part of the mantle above and including the transition zone the upper mantle.

(3) The core: which is subdivided into the inner and outer core.

Why D"?

You may already be wondering where does this name D" (dee double prime) come from? One of the early models of the Earth was devised by Keith Edward Bullen and published in 1942. He divided the Earth into a series of 7 shells labeled A through G. The crust was layer-A and inner core was layer-G. The whole lower mantle (a ~2000 km thick layer) was called layer-D. By 1950 Bullen found that a zone ~200 km thick in the lower mantle was distinct. So, he divided layer-D into the layers D’ and D". Most of these layer names of Bullen’s were never adopted or received their own name, but the D" layer still remains.
In what follows, we will go into more detail about the composition of these layers.

1.2 Mechanical Structure

Another way to categorize Earth structure is by its mechanical behavior. The image below shows the structure divided in this manner. Note, for reference the layers are still shaded by the compositional structure drawn in the previous section.
The major difference here is that now everything above the core is labeled by the three mechanical layers of i) **lithosphere**, ii) **asthenosphere**, and iii) **mesosphere**. In the next sections we will define these further.

Note that the lithosphere includes all of the crust and some of the upper mantle. The asthenosphere is located entirely within the upper mantle. The rest of the mantle is termed the mesosphere. The following table summarizes the mechanical boundary layers and their mechanical behavior.

<table>
<thead>
<tr>
<th>Mechanical Layer</th>
<th>Mechanical Behavior</th>
<th>Includes these compositional layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithosphere</td>
<td>Hard Solid</td>
<td>Crust and some of the upper mantle</td>
</tr>
<tr>
<td>Asthenosphere</td>
<td>Soft Solid</td>
<td>In the upper mantle</td>
</tr>
<tr>
<td>Mesosphere</td>
<td>Hard Solid</td>
<td>Some of the upper mantle, transition zone, and lower mantle including the D” layer.</td>
</tr>
<tr>
<td>Outer Core</td>
<td>Liquid</td>
<td>Outer Core</td>
</tr>
<tr>
<td>Inner Core</td>
<td>Hard Solid</td>
<td>Inner Core</td>
</tr>
</tbody>
</table>
2. Upper Mantle

2.1 Compositional Structure

Now let’s look at these various layers in a little more detail. A drawing zoomed a little closer into the crust might look like:

Very loosely speaking the composition of the lower crust is granitoid and lower oceanic crust is gabbro (basalt). The following figure from Lowrie [2007] gives a generalized picture of the composition of the oceanic crust.

Fig. 3.85 Generalized petrological model and P-wave velocity-depth profile for oceanic crust.
It is more difficult to try and make a generalized picture of the continental crust, but here is one such image (also from Lowrie).

![Diagram of the continental crust with P-wave velocity as a function of depth.](image)

**Fig. 3.86** Generalized petrological model and P-wave velocity–depth profile for continental crust (after Mueller, 1977).

In these figures you note that the uppermost mantle is listed as being composed of ultramafics. The next figure will help remind you of what ultramafics are.
The uppermost mantle primarily composed of peridotite, where the typical mantle peridotite composition is shaded in green in the above diagram. The most common model of the upper mantle composition is called the pyrolite model (PYRoxene + OLivine). This was originally derived from the composition of carbonaceous meteorites. The pyrolite model matches quite well with the composition of peridotites (which we have samples of that have erupted from the uppermost mantle), and we thus use peridotites as a plausible model of upper mantle composition. Recall that peridotite is ~75% olivine and 25% pyroxenes (clinopyroxene and orthopyroxene).

The compositional boundary between the crust and mantle is called the Moho, short for Mohoroviči who discovered it.
2.2 Mechanical Structure

Besides the compositional structure discussed above, there is also notable mechanical structure in the uppermost mantle. The physical state of materials depends on pressure (P) and temperature (T). Note that pressure increases linearly with depth in the crust and upper mantle (Figure from Lillie [1999]).

The temperature increase on the other hand is non-linear. That is, it rises quickly at shallow depths and more gradually at greater depths.
Note this temperature profile is termed the geothermal gradient. Or, the rate of increase in temperature per unit depth in the Earth.

So, what does this mean for peridotite which is the most abundant rock in the upper mantle? The next figure shows a P-T diagram for peridotite.

![Phase diagram for peridotite (Earth's mantle)](image)

Looking at this diagram we note 3 distinct regions:

1) Upper 100 km – peridotite is cold and solid. This is the region we define as the **lithosphere**.
2) ~100-350 km – peridotite is partially molten. This region is defined as the **asthenosphere**.
3) ≥ 350 km – peridotite has crossed back out of the partial melt region and is again solid. This region is defined as the **mesosphere**.

Materials that make up the asthenosphere tend to be slightly cooler than their melting point. This gives them a plastic-like quality. As the T- or P-on the material increases the material tends to deform and flow. Peridotite minerals with the lowest melting point (like feldspars and pyroxenes) melt and leave behind olivine crystals. This melt is trapped in unconnected interstitial pockets. Small amounts of trapped melt should explain the physical properties of the asthenosphere. Note that this only works if we have a small degree of melting. E.g., if we just have the melt distribution at the triple junctions but not at the grain boundaries, then we have no
physical connection of melt so that it doesn’t coalesce into a magma body and flow upward. The next figure from Blatt and Tracy [1996] may help to clarify this.

**FIGURE 7-9**

Schematic illustration of how melt can be distributed among solid grains in a partially molten aggregate such as mantle peridotite in the asthenosphere. (A) Small degrees of melting, allowing wetting only of the triple junctions but not of the grain boundaries. (B) Higher degrees of melting in which melt has moved out from triple junctions along grain boundaries to such an extent that all triple junctions are connected and a three-dimensional network of melt is created.

Redrawing our near surface diagram:
Here’s another figure demonstrating this concept in comparison to an Oreo cookie [Lillie, 1999].

**FIGURE 2.8** The relatively high temperatures and low pressures of the mantle between about 150 and 400 km create a special situation (Fig. 2.7), analogous to the soft creamy filling of an Oreo® cookie. Lithospheric plates ride over the softer asthenosphere. Crust forms the top part of the lithosphere; oceanic crust is substantially thinner than continental crust. While the chemical boundary between the crust and mantle (“Moho”) is sharp, the change in physical state between the lithosphere and asthenosphere is more subtle. The transition from asthenosphere to mesosphere is a broad zone of increasing strength.

3. **Transition Zone – Compositional Structure**

A simplified picture of the transition zone looks as follows.

**UPPER MANTLE**

\[ \text{Mg}_2\text{SiO}_4 \text{ - olivine structure} \]

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410 km (compositional boundary)

**TRANSITION ZONE**

\[ \text{Mg}_2\text{SiO}_4 \text{ - spinel structure} \]

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660 km (compositional boundary)

**LOWER MANTLE**

\[ \text{Mg}_2\text{SiO}_4 \rightarrow \text{MgSiO}_3 + \text{MgO} \]
The key points are:

1) The predominant mineral in the upper mantle is olivine. Recall, olivine in the mantle lies between 2 end members forsterite (Mg$_2$SiO$_4$) and fayalite (Fe$_2$SiO$_4$). Normal mantle olivine is mostly forsteritic, i.e., probably 91-94% Mg.

2) At ~410 km depth olivine undergoes a solid-solid phase transition from an olivine to a spinel structure. This transition does not involve a change in chemical composition, but a reorganization of the atoms into a different crystalline structure. This involves a closer packing of the atoms into a denser structure, giving rise to a ~10% density increase.

3) At ~660 km depth Mg$_2$SiO$_4$ breaks down into: (a) MgSiO$_3$ – perovskite structure (Pv) and MgO – pericline. These are also denser phases providing about another 10% increase in density.

Note that the mineral perovskite was recently renamed bridgmanite (http://science.sciencemag.org/content/346/6213/1100). Before a mineral can be officially named a naturally occurring sample of the mineral must be found. This sample was actually found in a meteorite in 2014. In many books and papers you will typically see the older name of perovskite.

Because Fe can also substitute into Mg we often write (Mg,Fe)O instead of just MgO. Then we talk about ferropericline rather than just pericline. But, because FeO is called wüstite, sometimes (Mg,Fe)O is also referred to as magnesiowüstite. A lot of names for essentially the same thing.

Here’s a table from Stacey and Davis [2008] showing the major phase transitions in olivine. Note that this table shows olivine transforming first to β-spinel (at 410 km depth) and then into γ-spinel (at 520 km depth). The existence of another global discontinuity at 520 km is still debated.
4. Lower Mantle – Compositional Structure

Here’s a simplified picture of the lower mantle.

The key points here are:

1) There is a boundary called the D'' discontinuity, which may be associated with the top of the D'' region. However, it is still not known whether this discontinuity is a global feature. This is because it can only be detected with seismic waves which do not provide global coverage.
2) In 2003 a solid-solid phase transition was discovered where perovskite (Pv) (now called bridgmanite) transforms into a denser post-perovskite structure (pPv). This transition provides about a 2-3% increase in density. It is possible that this phase transition is responsible for the D'' discontinuity and is currently an active area of research.

Here’s a picture of the post-perovskite structure (from its discoverer Kei Hirose):

![Post-Perovskite Structure](image)

5. Core

Determination of the composition of the core is more difficult to ascertain as we don’t have any samples from the core. Knowledge about core composition comes from two main lines of evidence:

1) Composition of meteorites. The Earth is believed to be formed from the accretion of meteorites. Meteorites are classified as:

   a) Stony (e.g., chondrites and achondrites) – which are similar to the mantle in composition.
   b) Iron – possibly the core is similar in composition to the iron meteorites (i.e., mostly Fe and some Ni).

   ![Seymchan Meteorite](image)

2) Seismic velocity and density structure. This provides more direct evidence as we can use seismic waves to directly probe the core structure. What we learn from seismology is that the inner core is almost pure Fe, and the outer core is mostly Fe with some lighter elements. Seismology has provided us with the density of the core material and we find that the outer core is approximately 10% less dense than pure Fe. The percentage of light elements shown in the figure above (S and Ni) is just one model of the outer core composition.
The figure below shows some of the different classes of meteorites and where we think they originated from. Basically, we think that many types of meteorites originated from asteroids or proto-planets that may have broken up. Achondrite stony meteorites are thought to have originated from the mantles of these proto-planets, Iron meteorites are thought to have originated from the cores of these proto-planets. Rare meteorites called Pallasites are thought to be from the core-mantle boundaries of these proto-planets.

References